Cosmic Abundance of Boron

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The abundance of boron is of considerable interest, but is difficult to determine. Boron undergoes thermonuclear destruction in stellar interiors, and hence is not a normal product of stellar nucleosynthesis. Thus its abundance is low, and until now it has seemed possible to understand its production in nature as a consequence of cosmic ray bombardment of the interstellar medium[1]. We point out here that the cosmic abundance of boron has been greatly underestimated, and that the upward revision of its abundance has important consequences in several areas of astrophysics.

In this article, we shall express all abundances relative to 10^6 atoms of Si. This requires conversion of abundances relative to 10^{12} atoms of H, using the factor 0.03175 (A. G. W. C., unpublished).

An average abundance of boron in ordinary chondrites[2,3] is 6.2. Boron is very difficult to measure quantitatively in meteorites, but recently it has become apparent that the boron abundance is highly variable, and in particular that the abundances in carbonaceous chondrites are very much higher than those in ordinary chondrites[4]. A. G. W. C. based his 1968 table of abundances[3] as much as possible on those in type I carbonaceous chondrites, or C1 chondrites, on the grounds that the more volatile elements are depleted relative to C1 abundances in all other types of chondrites. Thus the C1 meteorites have seemed to him to be the least fractionated source of abundances of the elements in the solar system apart from the Sun.

A spectrographic method[5] suggests an abundance of 126 for boron in a C1 meteorite. In four colorimetric analyses of two C1 meteorites, Mills[6] found an average abundance of boron of 5.7 parts per million, with a concentration range of 5.1 to 7.1 p.p.m., and a resulting abundance of 144. Using a fluorimetric technique, Quijano-Rico and Wanke[7] obtained an abundance of 186 for boron in one C2 meteorite, and an abundance of 121 in three C3 and C4 meteorites. A straightforward average of these values indicates a boron abundance of about 140. But the seeming constancy of these values of the boron abundance among the carbonaceous chondrites is inconsistent with the great depletion of boron in ordinary chondrites, as we shall discuss. This has motivated us to make a cosmochemical analysis of the condensation conditions for boron in a low pressure gas of solar composition, such as may have existed in the primitive solar nebula from which meteoritic materials condensed.

Because some of our discussion relating to the boron abundance in the Sun requires knowledge of the abundance of beryllium, we also discuss that abundance. Beryllium has an abundance much less variable in chondritic meteorites than boron, the average abundance in ordinary chondrites[2,3] being about 0.69. The preferred data on beryllium were published by Sill and Willis[8] who measured only one carbonaceous chondrite of type C2 and found an abundance of 0.81. This value has been adopted tentatively within the cosmochemical analysis we discuss here.

Condensation of Boron and Beryllium

Recent attempts[9-13] at predicting the behaviour of the elements during the condensation of the solar nebula have been based upon theoretical studies of the sequence of condensation of minerals from a cooling, low-pressure gas of solar composition. Be has been ignored in these thermodynamic calculations and the only work on B to date indicates it should not have condensed above 1,700 K at a partial pressure of hydrogen in the solar nebula of 0.5 atm (ref. 9).

Grossman[13] assumed that each condensate in the solar nebula remained in complete chemical equilibrium with the vapour, allowing a prediction of the variation of the principal element composition of the co-existing vapour with falling temperature. He solved the full equations only at temperatures greater than 1,200 K at 10^{-3} atm in that study, but we use the extrapolated vapour composition data at the lower temperatures required for B condensation, because less than 10% of the total condensable matter was left in the vapour state at 1,200 K. The presence of trace quantities of B and Be has a negligible effect on the principal element composition of the vapour.

Of forty-eight gaseous molecules containing boron for which thermodynamic data are readily available[14], only HBO_2, H_3BO_3, $NaBO_2$, and KBO_2 were found to be important in the temperature range of interest. Using a boron cosmic abundance of 140, we investigated the condensation temperatures of the crystalline phases KBO_2, HBO_2, H_3BO_3, $NaBH_4$, BN, $NaBO_2$, TiB, MgB_2, B_2O_3, TiB_2, $K_2B_6O_7$, MgB_4, $Na_2B_4O_7$, $K_2B_6O_{10}$, $B_{10}H_{14}$, $H_4B_2O_4$, and CB_4. Because of the relative stabilities of both gaseous and crystalline $NaBO_2$ and KBO_2, the principal difficulty in determining the condensation temperature of boron arises from uncertainty in the pressures of Na and K, two of the uncondensed elements at 1,200 K. Selecting a range of four orders of magnitude in each of the partial pressures of Na and K leads to a range of B condensation temperatures between 759 and 745 K (as $NaBO_2$) at a total pressure of 10^{-3}. These calculations assume that the most stable gaseous compounds and the highest condensing crystalline compounds of B in a solar gas have been considered and that B does not condense in solid solution at higher temperature.

We applied the same type of calculation to Be, assuming a cosmic abundance of 0.81. $Be(OH)_2$ and BeOH are the dominant gaseous species in the 1,200 to 1,800 K range. Be is almost totally condensed as $BeAl_2O_4$ in solid solution in spinel at 1,400 K. Again we assume that no important gaseous or crystalline species have been omitted from the consideration.

Many moderately volatile elements such as Mn, the alkalis, Cu, Au, Ga, and Ge exhibit abundance anomalies in the different classes of carbonaceous chondrites. In the C2 and C3 meteorites their concentrations, relative to Si, are all about 0.55 and 0.33, respectively, of their abundances in C1 meteorites. These relatively constant abundance depletions have been discussed in detail by Larimer[10,15] and Anders[15–17]. They have proposed that the carbonaceous chondrites are mixtures of fine-grained matrix material which remained in condensation equilibrium with the nebula down to ~350 K, and chondrules and metal grains which stopped equilibrating with the nebular vapour between 1,150 K and 1,250 K at 10^{-4} atm total pressure. The results obtained by Grossman[13] suggest that these temperatures should be 75 K lower. The low temperature matrix thus contains its full complement of the fractionated elements and the high temperature chondrules are devoid of them. The C1 meteorites are almost entirely matrix material and the average chondrule/matrix ratios in the C2 and C3 meteorites are in the ranges required by this model to account for the observed abundance depletions.

At 10^{-4} atm, Be would have condensed at about 1,325 K, somewhat above the maximum condensation temperatures, 1,075 to 1,175 K, of the fractionated elements. Thus, Be should not be fractionated among the carbonaceous chondrites and the abundance in the C1 meteorites must be very close to that in the C2 meteorites, 0.81. Boron, however, would have condensed at about 700 K at 10^{-4} atm and should, therefore, be classed among the volatile elements which are fractionated between the different types of carbonaceous chondrites. Indeed, abundance data[7] indicate that the ratio of boron in C2 to that in C3 and C4 meteorites is 1.54, which is within 10% of the average ratio, 0.55/0.33, observed for the other volatile elements. This suggests strongly that the abundance of boron in C1 meteorites could be calculated from the C2, and the C3 and C4 abundances, by dividing them by 0.55 and 0.33 respectively. yielding boron abundances of 339 and 367. If the boron abundance is increased by this much over that used in the condensation calculation, the condensation temperature is increased by only about 25 K, which is unimportant for the purposes of this computation.

It is thus our opinion that the boron abundances in C1 meteorites found by Harder[5] and by Mills[6] are too low, and we therefore adopt a value of 350 for the cosmic abundance of boron. We emphasize that it is highly desirable that this conclusion should be checked by better analyses of boron in C1 meteorites. For beryllium we adopt the C2 abundance of 0.81 as the cosmic abundance.

Boron in the Interstellar Medium

A tentative determination of the abundance of boron in the interstellar medium was made following a rocket ultraviolet measurement (A. M. Smith and T. P. Stecher, unpublished). In this work a feature at 1,362.46 Å in the spectrum of Zeta Ophiuchi was identified as interstellar boron II. A curve-of-growth analysis indicated a ratio of boron to oxygen in the interstellar medium of 1.9×10^{-5}. An oxygen abundance of 2.15×10^{7} yields a boron abundance of 418. Although one must be cautious about accepting abundance determinations based on measurements of only one line, it is interesting that this boron abundance is in essential agreement with that which we deduced in the preceding section. It is to be hoped that this matter can be investigated further with Copernicus.

Abundances in the Sun

The situation concerning the abundance of beryllium in the Sun has been summarized recently by Hauge and Engvold[18]. Their abundance values have been converted to the silicon scale. The beryllium abundance is derived from the BeII resonance doublet at 3,131 A. One of the lines is seriously blended and should not be used for abundance analyses. Beryllium abundances in the Sun were found in 1968 to be 0.47 by Grevesse[19] and 0.29 by Hauge and Engvold[20], and in 1970 Muller obtained a still lower abundance of 0.20 (quoted in ref. 18). From this last value one would conclude that beryllium is depleted to 0.25 of its normal cosmic abundance in the material at the solar surface, although we emphasize that one must be very cautious in using abundances determined from only one spectral line.

The situation concerning boron in the Sun has also been discussed by Hauge and Engvold[18]. Boron has not been detected in the Sun. The strongest lines fall in inaccessible spectral regions. Grevesse[19] concluded that the boron abundance is less than 20 from the absence of two BI lines at 11,661 A. Engvold[21] concluded that the boron abundance was less than 10 following an unsuccessful search for the absorption band spectrum of the BH molecule in sunspots. We have checked to see whether any boron molecular species should be expected under the conditions in which sunspot spectra are formed, other than those considered by Engvold[21], and we conclude that no significant amount of boron can be hiding in some molecular form not considered by Engvold. From this it seems that boron in the surface layers of the Sun has been depleted by at least a factor of 35.

For comparison, we note that the abundance of lithium[22] in C1 meteorites is 49.5, which can be compared with the solar photospheric value[23] of 0.20. Thus the solar depletion factor is about 250.

There is a clear inconsistency among the solar abundances. Lithium, beryllium, and boron are all destroyed at hydrogen-burning temperatures in the central regions of the Sun. The rate of destruction of beryllium is intermediate between the rates at which the lithium and boron isotopes are destroyed. Therefore it seems necessary to conclude either that the one line in the solar spectrum from which the beryllium abundance has been obtained is really due to some other element, or that the boron abundance in the Sun is actually an order of magnitude greater than the upper limits which have been set by the several searchers for it. Because many different lines of boron and boron compounds have been searched for in the Sun, without success, we believe that the solar beryllium line is suspect and should be re-examined.

If we accept that beryllium and boron, as well as lithium, are strongly depleted in the solar surface layers, then an unexpected amount of mixing has taken place within the solar interior some time during the history of the Sun. Using the nuclear reaction rates tabulated by Fowler, Caughlan, and Zimmerman[24] we conclude that the destruction of beryllium and boron will occur on a time scale of 10^{7} to 10^{9} yr in the deep solar interior, provided the temperature is in excess of 5×10^{6} K. In a model of the Sun which had been evolved without mixing for 4.6×10^{9} yr, provided by D. Ezer, 75% of the mass in the interior is at a temperature greater than 5×10^{6} K. Hence almost all of the outer 25% of the solar mass has been replaced at some time by material coming from a much greater depth.

This raises some interesting questions concerning the helium isotopes in the Sun. In the evolved but unmixed model of the Sun, the ratio of ^{3}He to ^{4}He rises steadily with increasing radial distance from the centre of the Sun, reaches a maximum at a temperature of 7×10^{6} K at a point at which approximately half the mass is contained within the interior radial distance, and then decreases toward the low initial value in the solar surface layers. The maximum value of the ratio is 0.17, which is orders of magnitude greater than the ratio of the isotopes observed in the solar wind.

So mixing within the solar interior cannot have brought material from near the centre to the surface in recent times, or the ratio of the helium isotopes would be much greater in the solar wind that the observed values[25] which are about 4×10^{-4}. This suggests that the extensive mixing within the solar interior occurred rather early in its history, before the ^{3}He had had time to build up a substantial abundance following the onset of the proton-proton thermonuclear reactions. One possible mechanism which seems consistent with this requirement is the operation of Eddington-Sweet circulation currents in the Sun[26,27], which would be quite rapid if the initial Sun were spinning at an angular rate nearly sufficient to produce rotational instability at the equator. Such circulation currents would be shut off when the Sun developed a substantial gradient in the mean molecular weight following conversion of hydrogen to helium near the centre.

Because of these considerations we think it is dangerous to make the common assumption that the abundance of ^{3}He in the surface layers of the Sun represents the sum of the initial abundances of ^{3}He and deuterium in solar material. The abundance of ^{3}He may have been modified by the mixing process.

Boron Production by Cosmic Rays

One of the seemingly more successful theories of recent years has been that of Reeves, Fowler, and Hoyle[1], who found that cosmic ray bombardment of the interstellar medium could successfully account for the abundances of the light elements in the solar system. This theory, in its more recent refinements[28–31], seems to account quantitatively for the production of ^{6}Li, ^{9}Be, ^{10}B, and ^{11}B. It did not produce enough ^{7}Li to agree with the observed abundance of that isotope, but there are other possible astrophysical sources which can produce this[32]. The theory accounted for the older low values of the boron isotope abundances.

The great upward revision of the boron abundance requires modifications to this theory. We emphasize that the cosmic ray production theory continues to account quantitatively for the abundances of ^{6}Li and ^{9}Be. But an additional mechanism must be found which can produce the boron isotopes.

We note that Fowler, Reeves, and Silk[28] have argued that a large flux of low-energy cosmic rays ($\sim$5 to 10 MeV) could not exist in sufficient quantity to heat the interstellar medium, because this flux would have produced too much boron. The new boron abundance is so much higher than the old one that this restriction on heating of the interstellar medium by a hypothetical flux of low-energy cosmic rays is now removed. Instead, one should ask whether the hypothetical flux of low energy cosmic rays might be the necessary mechanism to produce the additional boron.

Boron-10 is produced by the reaction ^{13}C(p,α)^{10}B, which has a Q value of -4.063 MeV. Boron-11 is produced by the reaction ^{14}N(p,α)^{11}C, which has a Q of -2.922 MeV. The abundances of ^{13}C and ^{14}N in the interstellar medium seem to have the same relative values as in the solar system[33]. Thus, in order to produce the solar system ratio of the boron isotope abundances, it is a necessary condition for the validity of the low-energy cosmic-ray bombardment hypothesis that the cross-section for the production of ^{10}B from ^{13}C, properly averaged over a cosmic-ray bombardment spectrum, should be higher than that for the production of ^{11}B from the proton bombardment of ^{14}N by a factor of 6.8. D. Bodansky provided unpublished cross-section data on the reaction ^{13}C(p,α)^{10}B and J. W. Truran informs us that, according to these data, the ratio of the average cross-sections for the two reactions is much less than 6.8.

Thus we conclude that it is no longer possible, from boron abundances, to argue that the heating of the interstellar medium may not occur primarily from a flux of low-energy cosmic rays. Such a flux may contribute significantly to the production of the boron isotopes, but we conclude that it is not the principal contributor to the production of these isotopes.

Boron Production from Supernovae

One of us[34] has recently prepared an extensive analysis of the structure of shock waves in supernova explosions, demonstrating that this structure may give rise to the production of the deuterium in the Galaxy through spallation of the helium contained in the outer parts of the supernova envelope. A substantial production of the boron isotopes should also occur under these circumstances. We give a brief account of the analysis here.

If a supernova explodes as a result of a nuclear detonation process in which about 1 MeV per nucleon is produced, and this supernova contains an extended atmosphere of hydrogen, essentially in a red giant configuration, then as the supernova shock wave progresses through this atmosphere, the rapidly decreasing density in the envelope will result in a strengthening of the shock wave. If the only constituent in the material traversed by the shock wave were the ions, the temperature of the ions behind the shock front would become progressively higher as the shock wave strengthens. Thus one would typically get ion temperatures of several MeV near the surface of the supernova envelope.

In fact, the energy behind the shock is shared between ions, electrons, and photons, and because of the low density most of the energy goes into the photons. The typical temperature behind the shock will be closer to one keV. But this asymptotic condition can only be approached gradually, because a very large number of photons must be created for each ion present, and these photons must then be heated.

The actual shock process starts with a heating of the ions in the shock front precursor by collision between the ions of the stationary gas and the ions moving in the shock surface. These collisions raise the ion temperature to several MeV. Energy is now fed from the ions to the electrons, which are heated to a temperature of about $m_e c^2$. Collisions between the electrons and the ions create photons by the bremsstrahlung process; most of the photons have very low energy. Collisions between the electrons and the low energy photons raise the average energy of these photons. The ion energy is thus channelled through the electrons into photons and, as the ion temperature gradually falls, the temperature of the electrons will eventually also fall as the system approaches thermal equilibrium.

The quantitative estimate indicates that it takes about 140 Compton collision periods for the initial high ion temperature to drop by about a factor of 2. During this time the collisions among the ions have brought about an approach toward a Maxwellian energy distribution; the distribution should be fairly accurately Maxwellian to about $4kT_i$, where T_i is the ion temperature, and beyond this there will be a gradual depletion of the high energy tail relative to the Maxwellian distribution. An ion temperature of about 10 MeV is sufficient to spallate most of the helium present in the medium, producing deuterium both directly and by way of the production of neutrons which are captured on the protons of the medium following the thermalization process.

The production of the boron isotopes from ^{13}C and ^{14}N has much lower spallation thresholds than that for production of deuterium from helium. Therefore we expect the production of the boron isotopes to take place at a much lower ion temperature than that at which the deuterium production takes place. This is fortunate, for otherwise the ^{10}B would be severely depleted by the neutrons that are produced in the spallation of helium. The ^{13}C and ^{14}N target nuclei may or may not have been enhanced in the outer envelope of the supernova during the preceding evolution of the star.

The situation is much more complex than in spallation processes taking place in the interstellar medium. The ion temperature remains high for a long enough period so that multiple nuclear reactions can take place on each affected nucleus. A reaction which is of obvious potential importance is $^{10}B(p,\alpha)^{7}Be$, which is exothermic with a Q value of 1.146 MeV. If, as we believe, this supernova production mechanism has been primarily responsible for the production of the boron isotopes in nature, then this secondary reaction may be primarily responsible for the production of ^{7}Li, which is formed following electron capture on ^{7}Be.

All of the product nuclei, ^{7}Be, ^{10}B, and ^{11}C, may be destroyed by further spallation reactions. Because it is possible that only a fraction of the produced material survives following the thermalization of the shock wave, because the cross-sections for destruction of the product nuclei are in general not known, and because the abundances of the target nuclei are uncertain, we do not feel in a position to predict the relative production of ^{7}Li, ^{10}B, and ^{11}B which results from the supernova shock process. The abundances of these product nuclei relative to the target nuclei, ^{13}C and ^{14}N, in the solar system, are of the same order as the initial deuterium abundance in the primitive solar nebula relative to the solar helium abundance. Thus it is not quantitatively implausible that the abundances of deuterium, ^{7}Li, ^{10}B, and ^{11}B, should all be produced in their solar system proportions in these supernova shock waves.

The review article on the meteoritic abundances of boron by Baedecker[4] first drew our attention to the necessity for this upward revision in the cosmic abundance of boron.

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1 Reeves, H., Fowler, W. A., and Hoyle, F., *Nature*, **226**, 727 (1970).
2 Urey, H. C., *Revs. Geophys.*, **2**, 1 (1964).
3 Cameron, A. G. W., in *Origin and Distribution of the Elements* (edit. by Ahrens, L. H.) (Pergamon, Oxford, 1968).
4 Baedecker, P. A., in *Handbook of Elemental Abundances in Meteorites* (edit. by Mason, B.) (Gordon and Breach, New York, 1971).
5 Harder, H., *Nachr. Akad. Wiss. Math-Phys. Gottingen*, **1**, 1 (1961).
6 Mills, A. A., *Nature*, **220**, 1113 (1968).
7 Quijano-Rico, M., and Wanke, H., in *Meteorite Research* (edit. by Millman, P. M.) (Reidel, Dordrecht, 1969).
8 Sill, C. W., and Willis, C. P., *Geochim. Cosmochim. Acta*, **26**, 1209 (1962).
9 Lord, H. C., *Icarus*, **4**, 279 (1965).
10 Larimer, J. W., *Geochim. Cosmochim. Acta*, **31**, 1215 (1967).
11 Gilman, R. C., *Astrophys. J. Lett.*, **155**, L185 (1969).
12 Fix, J. D., *Astrophys. J.*, **161**, 359 (1970).
13 Grossman, L., *Geochim. Cosmochim. Acta*, **36**, 597 (1972).
14 *JANAF Thermochemical Tables* (compiled by Thermal Research Lab., Dow Chemical Co., Midland, Michigan, 1960 and later).
15 Larimer, J. W., and Anders, E., *Geochim. Cosmochim. Acta*, **31**, 1239 (1967).
16 Anders, E., *Acc. Chem. Res.*, **1**, 289 (1968).
17 Anders, E., *Ann. Rev. Astron. Astrophys.*, **9**, 1 (1971).
18 Hauge, O., and Engvold, O., *Institute of Theoretical Astrophysics Report No. 31* (Univ. Oslo, 1970).
19 Grevesse, N., *Solar Phys.*, **5**, 159 (1968).
20 Hauge, O., and Engvold, O., *Astrophys. Lett.*, **4**, 143 (1968).
21 Engvold, O., *Solar Phys.*, **11**, 183 (1970).
22 Nichiporuk, W., and Moore, C. B., *Earth Planet. Sci. Lett.*, **9**, 280 (1970).
23 Engvold, O., Kjeldseth Moe, O., and Maltby, P., *Astron. Astrophys.*, **9**, 79 (1970).
24 Fowler, W. A., Caughlan, G. R., and Zimmerman, B. A., *Ann. Rev. Astron. Astrophys.*, **5**, 525 (1967).
25 Geiss, J., and Reeves, H., *Astron. Astrophys.*, **18**, 126 (1972).
26 Mestel, L., in *Stellar Structure* (edit. by Aller, L. H., and McLaughlin, D. B.) (Univ. Chicago Press, Chicago, 1965).
27 Iben, I., jun., *Ann. Phys.* (New York), **54**, 164 (1969).
28 Fowler, W. A., Reeves, H., and Silk, J., *Astrophys. J.*, **162**, 49 (1970).
29 Mitler, H. E., *Astrophys. Space Sci.*, **17**, 186 (1972).
30 Meneguzzi, M., Audouze, J., and Reeves, H., *Astron. Astrophys.*, **15**, 337 (1971).
31 Reeves, H., Audouze, J., Fowler, W. A., and Schramm, D. N., *Astrophys. J.* (in the press).
32 Cameron, A. G. W., and Fowler, W. A., *Astrophys. J.*, **167**, **111** (1971).
33 Wilson, R. W., Penzias, A. A., Jefferts, J. B., Thaddeus, P., and Kutner, M. L., *Astrophys. J. Lett.*, **176**, L77 (1972).
34 Colgate, S. A., *Astrophys. J.* (in the press).

Emission Mechanism in Pulsars

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In a new model of the emission from pulsars based on the relativistic beaming effect, the source of the radiation is the circular motion of high energy electrons round magnetic field lines. The radio emission at the gyrofrequency is from coherent bunches of electrons, and the optical and X-ray emission is the incoherent synchrotron radiation from the same electrons.

ALTHOUGH there is as yet no agreement on the location of the source of the pulsed radiation within the magnetosphere of a pulsar, there is now considerable evidence that it is located close to the velocity of light circle, so that the corotation of the magnetosphere moves the source with a velocity of the order of 0.8 to 0.9 c. The pulses are then formed by the process of relativistic beam compression[1-5], which allows the radiation process to be isotropic within the local frame of reference within the magnetosphere, giving a radiation beam solely due to the geometrical movement of the whole source.

Here I discuss the nature of the radiating source which the observations would require if the beaming effect is indeed primarily due to relativistic beam compression. I shall show that a simple and self-consistent model can explain the whole of the electromagnetic radiation from the Crab Nebula pulsar, including some of the more detailed characteristics of polarization and variability. The lack of optical pulses from other pulsars is also explained simply, as indeed it is on all other models so far put forward.

Characteristics of the Emitter

Although the Crab Nebula pulsar is the only pulsar known to radiate outside the radio spectrum, there is no reason to